Attitude Ground System (AGS) for the Magnetospheric Multiscale (MMS) Mission

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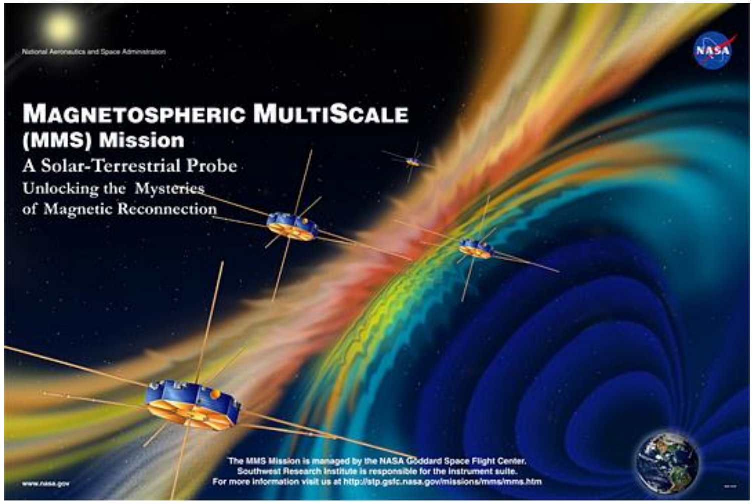


MMS Overview

- Recall from Conrad's presentation earlier today
- MMS launch: March 13, 2015 on an Atlas V from Space Launch Complex 40, Cape Canaveral, Florida
- MMS Observatory Separation: five minute intervals spinning at 3 rpm approximately 1.5 hours after launch
- MMS Science Goals: study magnetospheric plasma physics and understand the processes that cause power grids, communication disruptions and Aurora formation
- Mission: 4 identical spacecraft in tetrahedral formation with variable size
  - 1.2 x 12 R_E in Phase 1, with apogee on dayside to observe bow shock
  - 1.2 x 25 R_E in Phase 2, with apogee on nightside to observe magnetotail

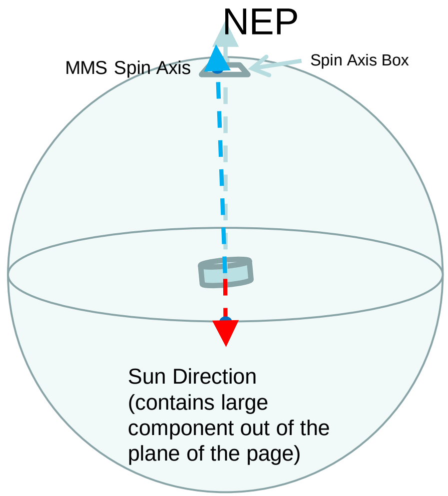
Challenges

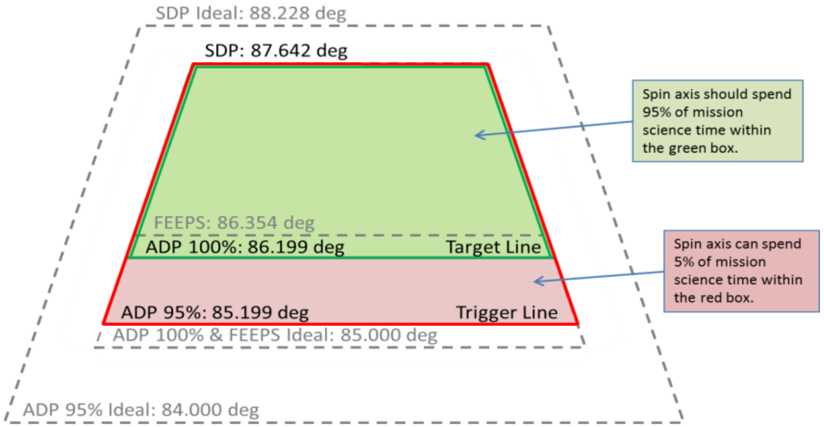
- Tight attitude control box, orbit and formation maintenance requirements

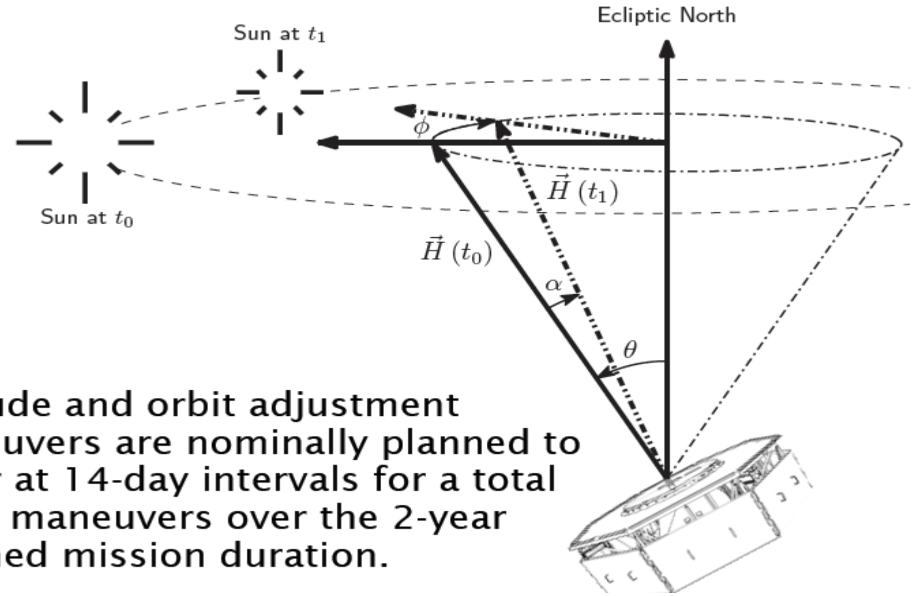
- Maneuvers on thrusters every two weeks
  - Delta-H
    - Spin axis direction and spin rate maintenance
  - Delta-V
    - Orbit and Formation maintenance
    - Mission phase transitions

- AGS support
  - Smart targeting prediction of Spin-Axis attitude in the presence of environmental torques to stay within the science attitude
  - Determination of the spacecraft attitude and spin rate (sensitive to knowledge of inertia tensor)
  - Calibrations to improve attitude determination results and improve orbit maneuvers
    - Mass properties (Center of Mass, and inertia tensor for nutation and coning)
    - Accelerometer bias (sensitive to the accuracy of the rate estimates)
    - Sensor alignments

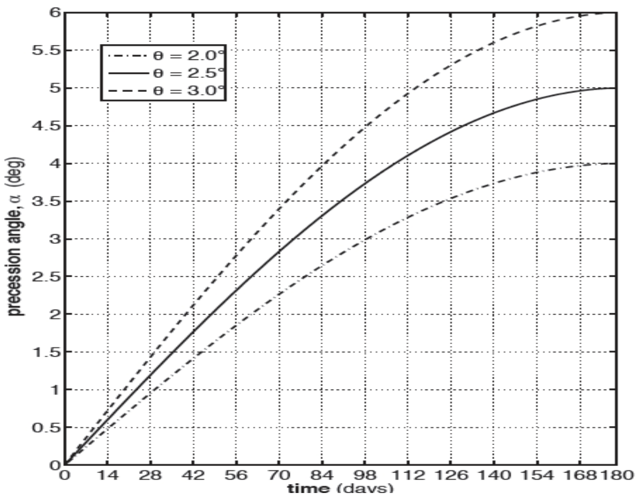
Spin-Axis Orientation and Control Box







$$\alpha(\Delta t) = \cos^{-1}\left[\cos\left(\dot{\phi}\Delta t\right)\sin^2\theta + \cos^2\theta\right]$$



- Attitude and orbit adjustment maneuvers are nominally planned to occur at 14-day intervals for a total of 52 maneuvers over the 2-year planned mission duration.

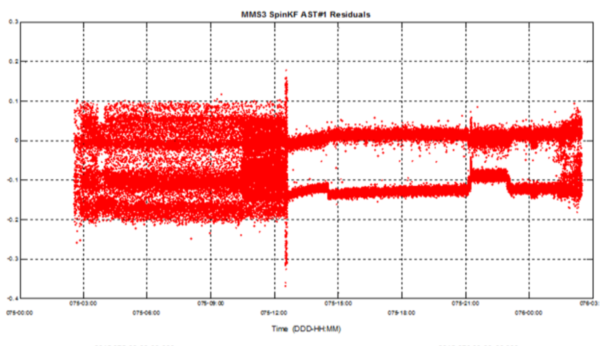
Attitude Ground System (AGS)

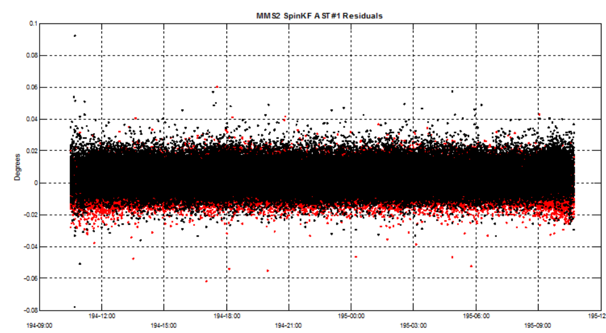
- MATLAB-based with a library of functionalities and core software from the Multi-mission Three-Axis Stabilized Spacecraft (MTASS) system
  - MTASS used at NASA/Goddard Space Flight Center to support a wide variety of missions

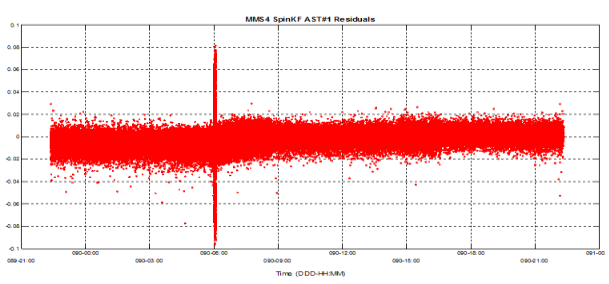
- Requirements:
  - Definitive attitude and spin rate history
    - 3-axis attitude solutions with accuracy of 0.1 deg, 3σ with star sensors
    - Spacecraft body rate accuracies (transverse) to meet accelerometer bias requirements
  - Accelerometer bias with an accuracy of 2 micro-g (3σ) with AMS
  - Validation of the onboard attitude, body rates, and accelerometer bias estimates
  - Prediction of spin axis attitude for 10 weeks with maneuver targeting capability
  - Sensor Interference prediction
  - Inertia tensor, center of mass, and sensor alignment calibrations
  - Trending of attitude, body rates, accelerometer bias, and mass property calibration results

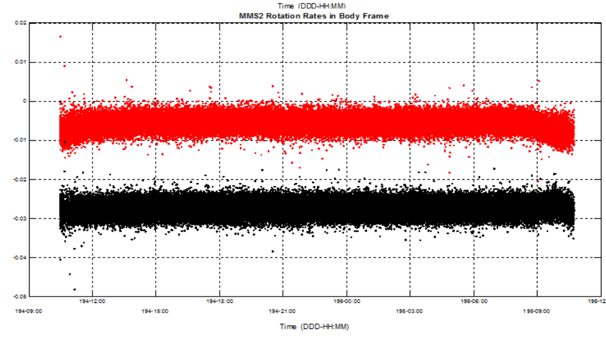
Attitude and Body Rate Determination

- "SpinKF"
  - 7 parameter state vector with angular momentum in body and inertial frames, and spin-phase instead of quaternion and rate
  - Accuracy better than 0.1 deg, 3σ on all three axes
  - Solutions highly dependent on the sensor alignment and inertia tensor (coning) calibration results



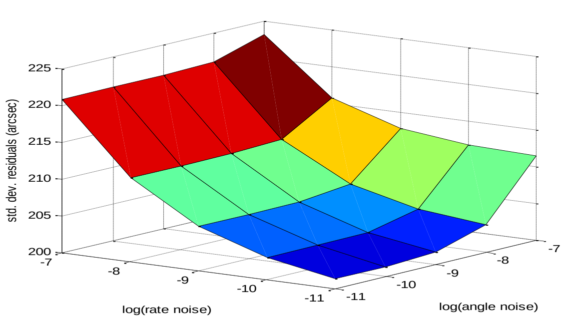


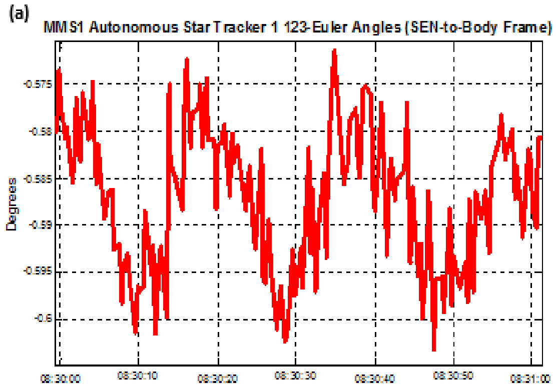


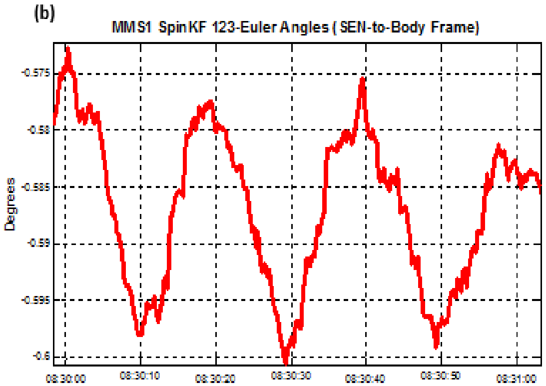


Kalman Filter Tuning

- Optimize SpinKF performance by adjusting the angle random walk and rate random walk parameters within the process noise
- Prior to launch:
  - using data from a simple rigid body MMS simulator and the MMS constellation high-fidelity simulator (CHIFI)
  - Standard deviations of the star camera residuals reduced by decreasing the rate random walk process noise by an order of magnitude
- After launch:
  - Star tracker transverse noise is near specification of 20 arc-sec.
  - Noise about the boresight approx. 3-times higher than expected
  - Improved Z-axis residual by 2-10% with star sensor noise parameter increased to 200 arc-sec depending on process noise parameter choice
  - Process noise parameters varied widely over several orders of magnitude



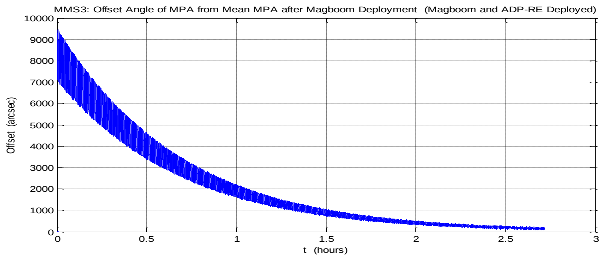




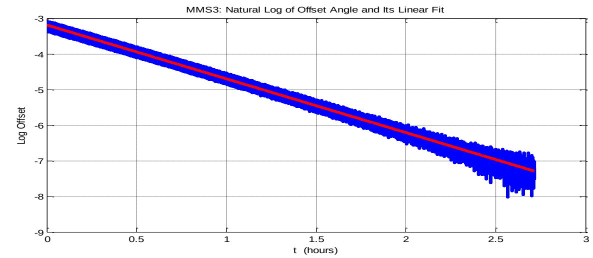
Nutation and Vibration Damping

- After damping, angular momentum aligned with major principal axis
- Causes of nutation and vibrations:
  - Thruster burns
  - Rapidly changing gravity-gradient torque every perigee pass
  - Spin-rate changes due to boom contraction/expansions from temperature changes upon entrance and exit of Earth’s shadows

Deployment Status	MMS1 Decay Time (hrs)	MMS2 Decay Time (hrs)	MMS3 Decay Time (hrs)	MMS4 Decay Time (hrs)
Mag Boom Deployed (SDP and ADP Stowed)	0.38	0.41	0.46	0.44
Mag Boom and SDP Deployed (ADP Stowed)	10.0	12.8	4.3	8.2
All Deployed	6.5	11.5	5.4	8.3



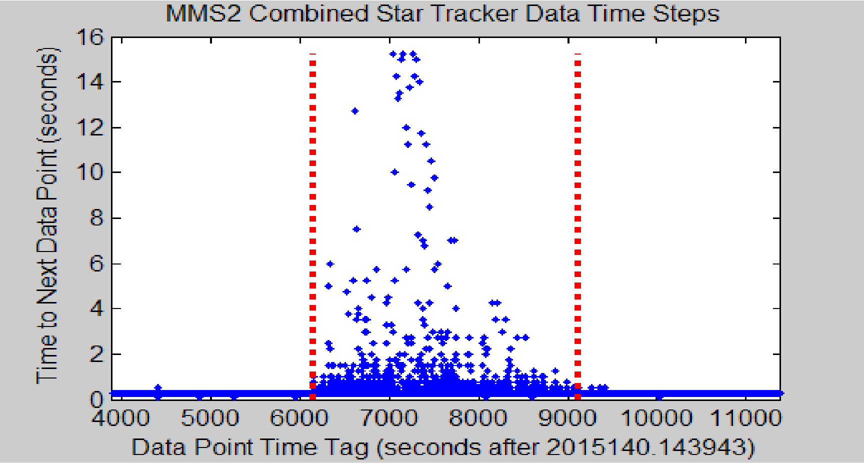
Example of MPA Offset Angles

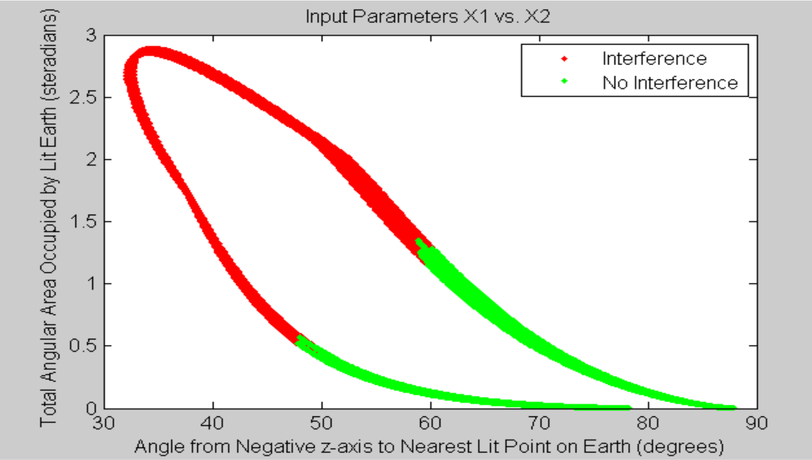


Logarithm of the MPA offset angle and its linear fit (red line).

Earth Albedo Sensor Interference

- Unexpected periodic star tracker interference post -Z-axis ADP boom deployment
- Higher incident of flagged bad data points from the star tracker
- Hypothesis: glint or diffuse reflection of sunlight and Earth albedo in the star tracker from the ADP boom
  - Interference not observed until deployment of -Z-axis ADP boom
  - Interference occurred near every perigee (max. effect of Earth Albedo)
  - Interference correlated with spin-phase correlated with geometry of spacecraft
- Time-dependent illumination from the spacecraft position relative to Earth

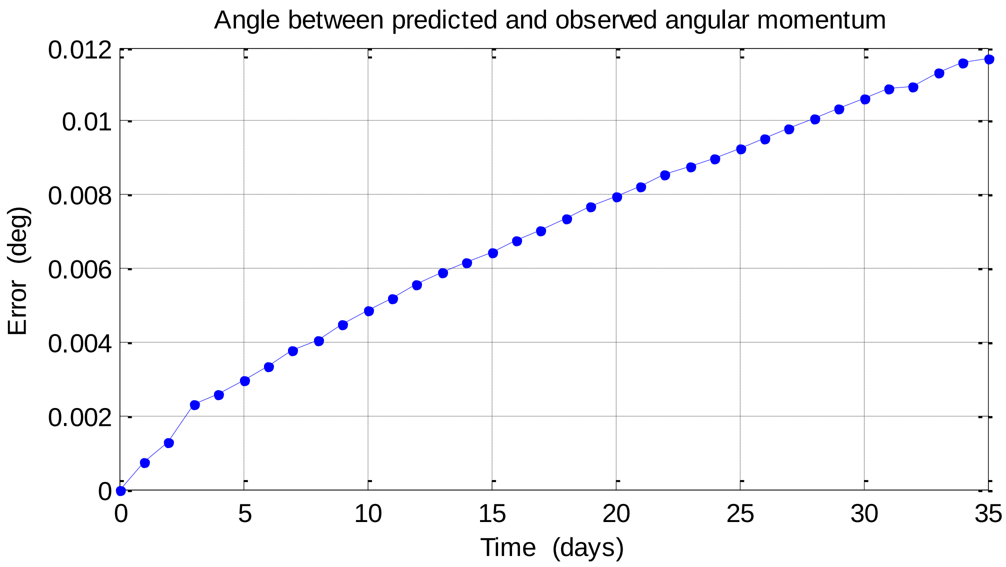




Spin-Axis Prediction and Maneuver Targeting

- 10-week prediction of spacecraft attitude and spin rate
- account for the Sun and target box geometry and the seasonally changing environmental torques
- Environmental Torque Model: spin-averaged and orbit-averaged gravity-gradient torque

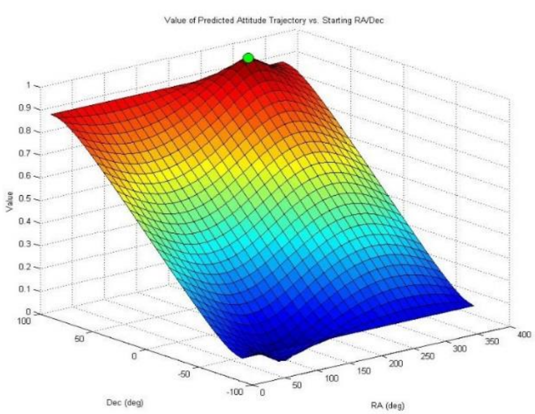
$$\boldsymbol{\tau}_{gg} = \frac{3}{2}\frac{\mu}{a^3(1-e^2)^{3/2}}(I_z - I_t)(\hat{\boldsymbol{Z}}\cdot\hat{\boldsymbol{h}})(\hat{\boldsymbol{Z}}\times\hat{\boldsymbol{h}})$$

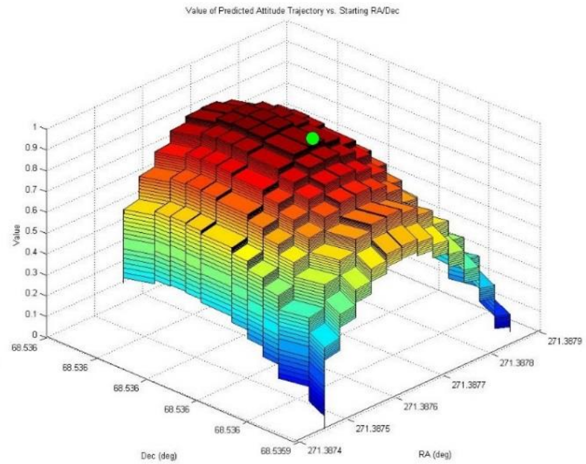


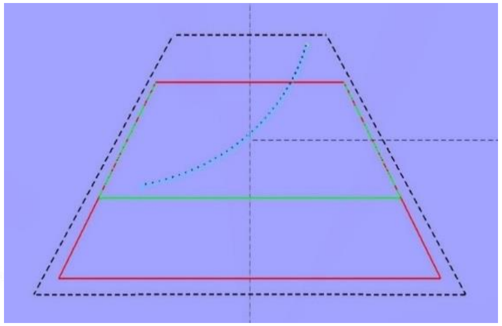
Shadow Period Attitude Optimization

- Shadow period means orbits with eclipse lasting more than 2 hours and lasting approx. two months
- No maneuvers to maintain power levels while assuring science attitude
- Achieve best possible attitude prior to last maneuver before shadow period
  - Minimize the angle between the spin-axis direction and center of the box over the duration of the shadow period

$$C = \left[\sum_{i=1}^{N} (\cos^{-1}(\boldsymbol{v}_i \cdot \boldsymbol{w}_i))^2 \right]^{1/2}$$







Spin-axis trajectory during shadow period

Conclusions

- AGS functionalities essential for MMS mission support
  - Onboard attitude and body rate validation
  - Star tracker alignment calibration
  - Major principal axis direction calibration (coning)
  - Smart targeting to for maneuver planning to maintain science attitude
- AGS capabilities enabled proper identification of error sources affecting attitude and body rate estimation, from thermal variations to sensor interference
- Special analysis to support the mission:
  - Long-term planning for long shadow periods
  - Earth Albedo Interference prediction due to unexpected star tracker sensor noise
- SpinKF performed very well despite the high dependency with accuracy of start tracker alignments and knowledge of inertia tensor
- Iterations between the star tracker alignment and inertia tensor calibrations due to their coupling
  - Star sensor alignments defined the body frame
  - Major principal axis direction calibration performed relative to the body gframe
- AGS predicted with high degree of accuracy (0.01 deg) the precession of the angular momentum for up to a month